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A MODERN THERMO-KINETIC WARM FOG DISPERSAL SYSTEM.(U)

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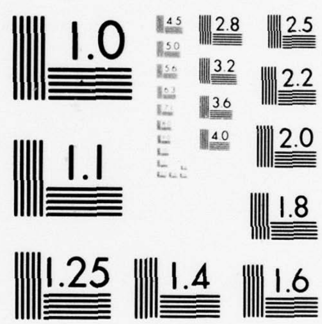
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A Modern Thermo-Kinetic Warm Fog Dispersal System

BRUCE A. KUNKEL

14 November 1978

METEOROLOGY DIVISION PROJECT 2093
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

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An extensive investigation has been made to arrive at optimum specifications for a thermo-kinetic warm fog dispersal system. This study included passive heat tests, sub-scale heat/momentum tests, and tests with a single full-scale runway combustor and an approach zone combustor. These tests were augmented with extensive analytical modeling of buoyant jets under coflowing and counterflowing wind conditions. The landing category and the operational requirements within each category are the primary factors cont

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20. Abstract (Continued)

affecting the size of the thermal fog dispersal system (TFDS). A Cat II TFDS employs 22 percent fewer combustors and uses 50 percent less fuel than a Cat I TFDS. The combustor specification and orientation are presented for both Cat I and Cat II systems.

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Preface

The author would like to thank the following people for their role in the Warm Fog Dispersal Program, for without their help this report would not be possible:

Dr. Bernard Silverman for initiating the program and providing leadership during the first phase of the effort.

Dr. Alan Weinstein, Mrs. Rosemary Dyer and Dr. Milton Klein for their many scientific contributions during various phases of the program.

Messrs. Edward Sprague, Frederick Brousaides, Stuart Sheets and George Travers for providing the technical support for the various field programs.

The personnel of Det 1, Hq ADTC/CEEDO for their program management effort during the combustor development phase of the program.

The personnel of Ultrasystems Inc., and particularly Mr. Charles Price, for their assistance and technical exchange of ideas throughout the seven-year effort.

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1. INTRODUCTION

Delays and diversions due to fog have plagued aviation since the first scheduled flights. The advent of jumbo jets with their huge cargoes and heavy fuel consumption has elevated the problem from a simple inconvenience to a serious economic and military concern. Weinstein[1, 2] has shown that fog can be expected to affect up to several percent of the annual commercial and military flights, with the absolute number of flights sometimes running into the thousands per year. Seven years ago Beckwith[3] estimated that fog was costing civilian domestic airlines over $75 million annually, and was expected to increase yearly. On rare occasions the losses are measured in lives as well as dollars. These economic and human factors have motivated an intensive search for methods of artificial fog dispersal.

The most recent review of the current state of the art of fog dispersal technology has been given by Weinstein,[4] drawing heavily on an older but more detailed

(Received for publication 14 November 1978)

1. Weinstein, A.I. (1974) Projected utilization of warm fog dispersal systems at several major airports, J. Appl. Meteor. 13:788-795.
2. Weinstein, A.I. (1975) Projected Interruptions in Airport Runway Operations Due to Fog, AFCRL-TR-75-0198.
3. Beckwith, W.B. (1971) The effect of weather on the operations and economics of air transportation today, Bull. Amer. Meteor. Soc. 52:863-868.
4. Weinstein, A.I. (1976) Fog dispersal: A technology assessment, J. Aircraft. 14:38-43.

survey by Silverman and Weinstein.[5] It is not appropriate to review these in detail here. Suffice it to say that dispersal of supercooled fog (that is, temperature $<0^{\circ}C$) is generally recognized to be an operational technology with programs existing in the U. S. (Fletcher,[6] Beckwith[3]) and Europe (Serpolay[7]). Warm fog (that is, temperature $\geq 0^{\circ}C$), however, is by far the most common visibility obscuration worldwide. This phenomenon has been the subject of the most intense weather modification research over the past few decades. Helicopter downwash mixing as described by Plank et al,[8] hygroscopic particle seeding as originally described by Houghton and Radford[9] and more recently by Weinstein and Silverman,[10] the use of electrical charging, some of which has been described by Tag,[11, 12] and the application of heat as originally described by Walker and Fox[13] are the four methods of warm fog dispersal that have been most vigorously pursued. The first three techniques have not been found to be well suited to routine operational implementation at large airports.

2. THERMAL FOG DISPERSAL

The application of heat to disperse fog is accomplished with an array of ground-based heat sources. These sources are used to warm the air, thereby raising its capacity to hold water vapor. If the air temperature is raised

5. Silverman, B.A., and Weinstein, A.I. (1974) Fog, Weather and Climate Modification, W.N. Hess, Ed., Wiley, 355-383.
6. Fletcher, R.D. (1971) Operational Applications of Fog Modification, Proc. Intern. Conf. Weather Modification, Canberra, Australia, 255-258.
7. Serpolay, R. (1960) Levons le Rideau des Brumes (lifting the fog curtain), Propane et Butane 12:46-55.
8. Plank, V.G., Spatola, A.A., and Hicks, J.R. (1971) Summary results of the Lewisburg fog clearing program, J. Appl. Meteor. 10:763-779.
9. Houghton, H.G., and Radford, W.H. (1938) On the local dissipation of natural fog, Paper Phys. Oceanogr. Meteor. 6(No. 3):63.
10. Weinstein, A.I., and Silverman, B.A. (1973) A numerical analysis of some practical aspects of airborne urea seeding of warm fog dispersal at airports, J. Appl. Meteor. 12:771-780.
11. Tag, P.M. (1976) A numerical simulation of warm fog dissipation by electrically enhanced coalescence: Part I. An applied electric field, J. Appl. Meteor. 15:282-291.
12. Tag, P.M. (1977) A numerical simulation of warm fog dissipation by electrically enhanced coalescence: Part II. Charged drop seeding, J. Appl. Meteor. 16:686-696.
13. Walker, E.G., and Fox, D.A. (1946) The Dispersal of Fog From Airport Runways, A Record of the Work of Technical Branch F Petroleum Warfare Dept. 1942-1946, Ministry of Supply, London.

sufficiently, the fog droplets will evaporate and the visibility will increase above take-off or landing minimums.

Considerable attention has been paid to this method of warm fog dispersal. Unfortunately, since little material has been published in the formal literature, it is difficult to document the work in a systematic way. I attempt here to briefly review the major efforts by subdivision into two categories according to the method of directing the heat.

2.1 Passive Systems

The first method of thermal fog dispersal that was investigated involved the simple liberation of heat from parallel lines of heat sources on both sides of a runway. This technique depends upon the dynamic circulation induced by the two lines of burners to merge the plumes over the runway. The most well known example of a passive thermal fog dispersal system is the English system that came to be known as Fog Investigations and Dispersal Operations, or FIDO. The FIDO program is described in great detail (unfortunately in a rather obscure publication) by Walker and Fox.[13] Important, independent, sub-scale studies relating to this effort were described by Rankine[14] and Rouse et al.[15] It was said by Walker and Fox that FIDO systems were operated at 12 installations in England between 1943 and 1945 and were responsible for 2500 landings.

Following the success of the English FIDO, a variation on this technique was developed at Arcata, California by the Landing Aids Experiment Station (LAES[16]). A system patterned after the LAES work was installed at Los Angeles International Airport (LAX) in 1949. Called LAX FIDO, that system was finally abandoned in 1953 after it was found to be too expensive to operate successfully for the traffic load and size of aircraft using LAX in the 1950's.

Approximately a decade after the LAX FIDO activities, some passive thermal fog dispersal experiments were conducted in Japan. As described by Magono,[17] these experiments verified the practical feasibility of operational thermal fog dispersal.

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14. Rankine, A.O. (1950) Experimental studies in thermal convection, Proc. Phys. Soc. Section B **63**:225-251.
15. Rouse, H., Baines, W.D., and Humphreys, H.W. (1953) Free convection over parallel sources of heat, Proc. Phys. Soc., Section B **66**:393-399.
16. Landing Aids Experiment Station (1950) Thermal Fog Dispersal Manual, Transocean Air Lines, Arcata, Ca. (Available from DOT; FAA, Report No. FAA-RD-72-138).
17. Magono, C. (1972) A warm fog dissipation experiment utilizing burning propane gas, J. Rech. Atmos. **VI**:343-365.

Recently, Kunkel et al[18] described a series of passive thermal fog dispersal experiments conducted in California which confirmed the earlier findings of the FIDO program with respect to the characteristic pattern of temperature rise in a crosswind situation. The program also documented visibility improvements in the heat plumes that could only be inferred from the published FIDO data on temperature rise. Tag and Lowe[19] recently reported on numerical simulations of passive thermal fog dispersal that could lead to extension of the past field results to a wider range of meteorological conditions.

2.2 Thermo-Kinetic Systems

The alternative to a passive system is one that uses thrust to direct the heat plume over its intended target. The best known system that uses this technique is a French one called Turboclair. As described by Sauvalle,[20] this system uses surplus jet aircraft engines aligned on one side of the runway to supply the heat and thrust. Turboclair systems were credited with assisting 128 low visibility landings during the 1976/77 winter fog season at Orly and Charles DeGaulle Airports near Paris.

The first experience with thermo-kinetic fog dispersal in the U.S. was described by Appleman and Coons.[21] In this pilot project the exhausts from four C-141 aircraft were used to raise the visibility from 300 m to well over 800 m along the runway at Travis AFB.

Starting in 1971 the Air Force Cambridge Research Laboratories (now known as the Air Force Geophysics Laboratory) initiated a program to develop an efficient and effective thermo-kinetic fog dispersal system. This paper describes that program and presents a set of specifications for a thermo-kinetic fog dispersal system.

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18. Kunkel, B.A., Silverman, B.A., and Weinstein, A.I. (1974) An evaluation of some thermal fog dispersal experiments, J. Appl. Meteor. 13:666-675.

19. Tag, P.M., Lowe, P.R. (1974) Fog Dissipation by Heat: A Numerical Study, Preprints Fourth Conf. on Weather Modification, Ft. Lauderdale, FL, 271-278.

20. Sauvalle, E. (1976) Operational Fog Dispersal Systems at Orly and Charles De Gaulle Airports Using the Turboclair Process, Second WMO Sci. Conf. on Weather Modification, Boulder, CO, 397-404.

21. Appleman, H.S., and Coons, F.G. (1970) The use of jet aircraft engines to dissipate warm fog, J. Appl. Meteor. 9:464-467.

3. CLEARING GEOMETRY

Before specifying the amount of thermal and kinetic energy required, the volume to be cleared must be defined. The size of the clearing volume is defined by the landing category and the operational requirements within each landing category. There are three landing categories: Category I (Decision Height (DH) = 60 m, Runway Visual Range (RVR) = 800 m), Category II (DH = 30 m, RVR = 400 m) and Category III (DH = 15 m, RVR = 200 m). The Air Force, for the most part, uses the Category I landing system even though some of their airfields and aircraft are equipped for Category II landing operations.

The geometry of the cleared volume, as defined by the Military Air Command (MAC), for a Category I and Category II landing system is shown in Figure 1 for a 45 m and 90 m wide runway. For a Category I clearing, the cleared zone is 75 m high, 150 m upstream of the decision height (DH) and tapers gradually to a height of 15 m at a point 900 m down the runway from the threshold. It continues at 15 m for the remaining runway length. The width of the cleared zone at the outer end of the approach is 45 m wider than the runway width (22.5 m on each side). It then tapers to the width of the runway at the touchdown point and continues at runway width for the full length of the runway. Table 1 shows the minimum

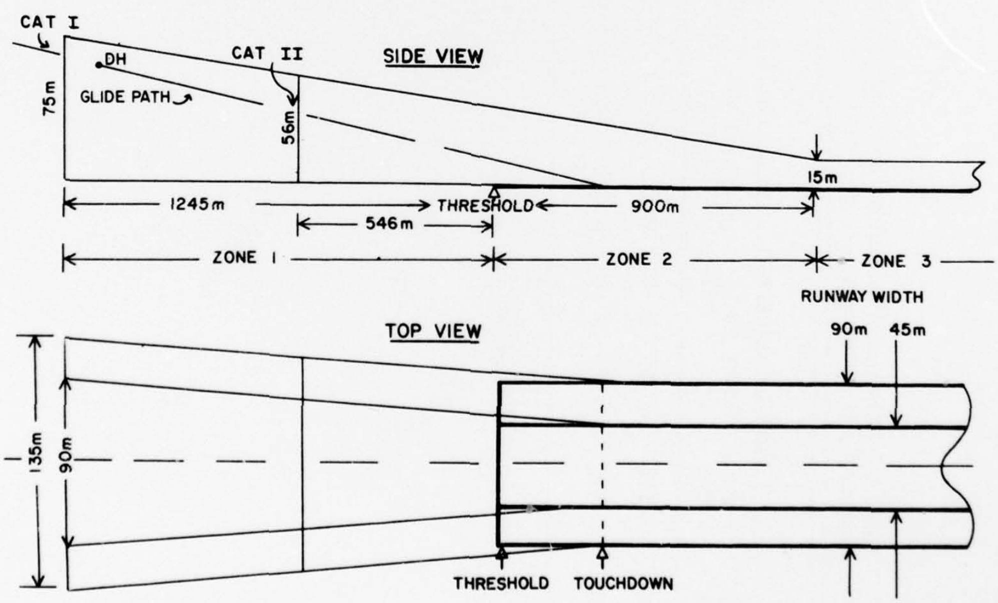

Figure 1. Cleared Zone Section Area

Table 1. Minimum Dimensions and Total Volume to be Cleared and RVR to be Provided for Ramstein AB, Germany

Type of Approach	Zone 1 - Approach				Zone 2 - Touchdown				Zone 3 - Roll Out				Total Clearing Volume (10^6 m^3)
	Length* (m)	Width (m)	Height (m)	RVR (m)	Length (m)	Width (m)	Height (m)	RVR (m)	Length (m)	Width (m)	Height (m)	RVR (m)	
Cat I	1245	63-90	40-75	800	900	45-63	15-40	800	1540	45	15	400	8.0
Cat II	546	63-70	40-56	400	900	45-63	15-40	400	1540	45	15	400	4.0

* assumes a 21/2^{o}glide slope.

dimensions of the clearing volume and the RVR for the two landing categories for Ramstein AB, the Air Force's leading candidate for a thermal fog dispersal system. The width of the runway at Ramstein AB is 45 m. It can be seen that twice as much volume must be cleared for a Category I as for a Category II landing system.

Six other Air Force bases were listed as potential candidates for a thermal fog dispersal system. These bases, the runway lengths and widths, and total clearing volume for a Category I landing system are given in Table 2.

Table 2. Runway Specifications and Category I Clearing Volumes for the Seven Candidate Bases

Base	Runway Length (m)	Runway Width (m)	Clearing Volume (10^6 m^3)
Ramstein	2440	45	8.0
Travis	3350	90	14.9
Castle	3600	90	15.3
March	4050	90	15.8
McGuire	3050	60	10.5
McChord	3080	45	8.5
Upper Heyford	2930	60	10.3

4. THEORETICAL HEAT AND FUEL REQUIREMENTS

In order to clear fog, sufficient heat must be provided to evaporate the fog droplets and to raise the air temperature sufficiently to accommodate the evaporated water in the vapor state. The amount of heat required to accomplish the former is directly proportional to the fog liquid water content. The amount of heat required for the latter is related to the temperature of the fog as well as the liquid water content.

Figure 2 shows the amount of heat required to completely clear fogs of different liquid water contents and at different temperatures. Any hydrocarbon fuel that would be burned to create the heat would also produce some water vapor. The solid lines in Figure 2 represent the heat requirements taking into account the water vapor from the burning fuel. The dashed lines show the heat requirements if the added water vapor from the fuel is neglected. The temperature rise required to evaporate the fog water is shown on the right. The temperature rise scale is

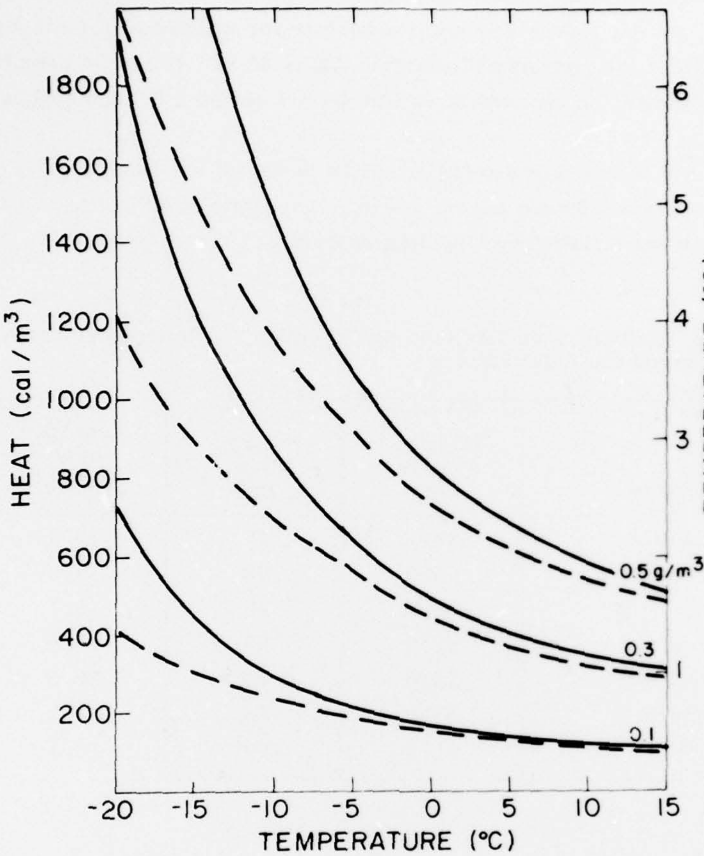

Figure 2. Heat Required to Dissipate Fog as a Function of Air Temperature and Liquid Water Content

approximate (±7 percent) since the temperature rise produced by a given quantity of heat is a function of the air density which varies slightly with temperature. The curves are based on an atmospheric pressure of 1000 mb.

Below 0^oC the heat requirements begin to rise dramatically, especially at the higher liquid water contents. Above 0^oC, the water vapor added by the burning fuel has little effect on the heat requirements. Below 0^oC, however, the added water vapor becomes increasingly more important. Because of the higher heat requirements for below freezing temperatures, thermal fog dispersal is normally considered a warm, rather than a supercooled, fog dispersal technique.

The curves in Figure 2 represent the heat requirements for total clearing. In reality, total evaporation need not be accomplished. Rather, only enough evaporation is needed to reduce the number and/or size of the droplets sufficiently to raise

the visibility above the Category I limit of 800 m or the Category II limit of 400 m. This must, however, be accomplished rapidly, as the wind will tend to carry the clearing away from its intended target if the clearing takes too long to develop.

It would appear from Figure 2 that a temperature rise of $2^{\circ}C$ would be sufficient to disperse most warm fogs. Fogs with liquid water contents greater than $0.3\ g/m^3$ are quite rare and would probably not be suitable for a thermal fog dispersal system because the extremely low visibilities would impede the taxiing of aircraft. For most visibility and wind conditions, a $2^{\circ}C$ temperature rise would provide a sufficiently rapid clearing, as shown by Kunkel et al.[18] This is below the $3.3^{\circ}C$ ($6^{\circ}F$) found during the FIDO experiments, but is close to the $1.6^{\circ}C$ assumed by Magono[17] and the 2-$3^{\circ}C$ reportedly aimed for by the Turboclair system.

Table 3 shows the amount of aviation fuel required to raise the air temperature $2^{\circ}C$ throughout the Category I and II clearing volumes at Ramstein AB.

Table 3. Fuel Requirements to Raise Air Temperature $2^{\circ}C$ for Categories I and II Clearing Volumes at Ramstein AB

Landing Category	Fuel (liter)
I	570
II	285

The actual amount of fuel required during a 5 min operation (the estimated time to land one aircraft) would be considerably greater since some heat will escape the clearing volume because of its buoyancy and the wind. Also, in practice, the heat cannot be distributed uniformly thus requiring a certain amount of overheating.

5. REVIEW OF USAF PROGRAM

In 1971, the Air Force Cambridge Research Laboratories initiated a program to develop an efficient and effective thermal fog dispersal system that would be compatible with a Category I landing system. The objective was to design a system that would efficiently distribute the heat as uniformly as possible throughout the clearing volume, thus minimizing fuel consumption. Passive heat tests,

described by Kunkel et al,[18] pointed out the inefficiency of a passive type system which depends quite heavily on the winds and requires large amounts of energy in order to insure adequate heating in the clearing volume. As a result, tests conducted on a 1/6 distance scale were performed in 1974 (Kunkel[22]). Blowers were used to project the heat from propane burners over a hypothetical runway. Tests were conducted in clear air and an array of thermistors and wind sensors were used to measure the heat plume profile under a variety of heat, thrust, and wind conditions. Froude number scaling laws were used to determine the heat and thrust requirements and combustor spacing for a full-scale thermal fog dispersal system. In the meantime, theoretical studies on the behavior of buoyant round and planar jets in a wind field were being conducted and were summarized in a series of publications (Klein and Kunkel,[23, 24] Klein[25, 26, 27]). As a result of these studies, combustor specifications were derived for a full-scale thermal fog dispersal system. Because of the inherent uncertainties in scaling up to full scale, the combustor specifications were inflated to provide a safety margin. A contract was awarded to Ultrasystems Inc., Irvine, CA, to design, fabricate and test one runway combustor and one approach zone combustor.

An artist's conception of the two combustors designed by the contractor is shown in Figure 3. The combustors each produce two exhaust flows of heated air directed toward the runway at various elevation angles. Each unit consists of a central diesel engine with propellers at each end to produce the combustion air and the thrust air. The air is heated as it passes by a burner located in front of each propeller, and then enters an elbow where it is turned 90°. The elbows rotate in the vertical to allow the thrust to be projected out at different elevation angles.

The runway unit is designed to be flush with the ground so as not to be a hazard to aircraft that might accidently veer off the edge of the runway. The approach zone combustor was designed for above-ground use. Table 4 lists the design and performance parameters of the two combustors. Thrust is specified

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22. Kunkel, B.A. (1975) Heat and Thrust Requirements of a Thermal Fog Dispersal System, AFCRL-TR-75-0581.

23. Klein, M.M., and Kunkel, B.A. (1975) Interaction of a Buoyant Turbulent Planar Jet With a Co-flowing Wind, AFCRL-TR-75-0368.

24. Klein, M.M., and Kunkel, B.A. (1975) Interaction of a Buoyant Turbulent Round Jet with a Co-flowing Wind, AFCRL-TR-75-0581.

25. Klein, M.M. (1977) A Method for Determining the Point of Lift-Off and Modified Trajectory of a Ground-Based Heated Turbulent Planar Jet in a Co-flowing Wind, AFGL-TR-77-0033.

26. Klein, M.M. (1977) Interaction of a Turbulent Planar Heated Jet with a Counterflowing Wind, AFGL-TR-77-0214.

27. Klein, M.M. (1978) Calculations of the Buoyant Motion of a Turbulent Planar Heated Jet in an Opposing Air Stream, AFGL-TR-78-0072.

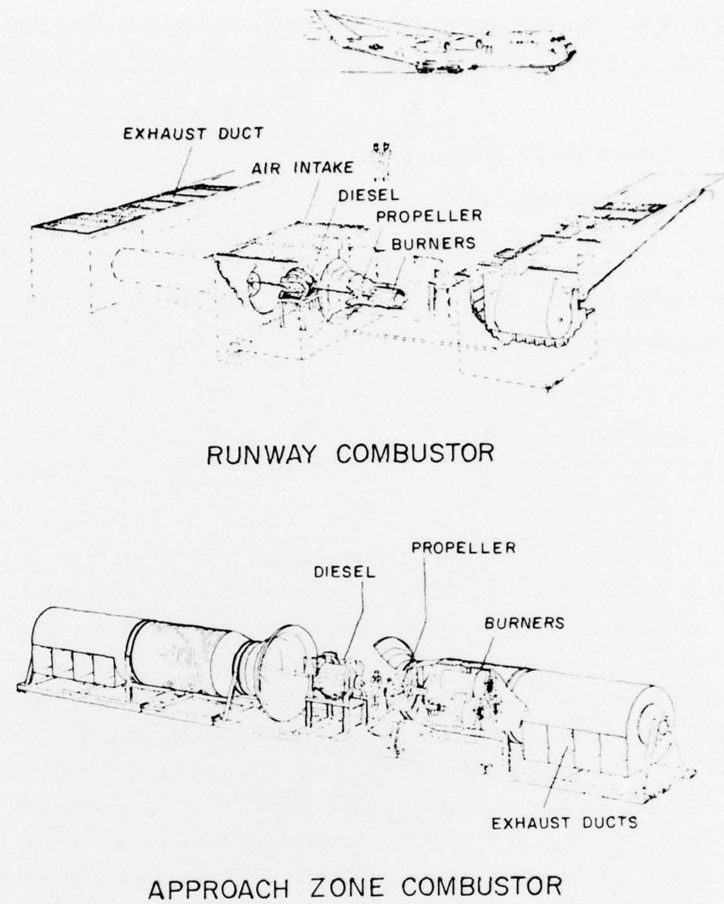

Figure 3. Artist Conception of Runway and Approach Zone Combustors

instead of velocity or momentum because theory shows that the plume projection distance is a function of the outlet area and the square of the outlet velocity. Thrust is also related to the area and velocity squared in the following manner.

$$\text{Thrust} = V^2 A \rho / g$$

where V, A, ρ and g are outlet velocity, outlet area, air density, and gravitational acceleration, respectively.

In June 1978, tests were conducted with the two combustors to verify or improve on the heat and thrust requirements as determined from the subscale tests conducted in 1974. The tests were conducted at the Ultrasystems test facility at

Table 4. Combustor Design and Performance Specifications

	Approach	Runway
Center - Center Outlet Distance (m)	23	18
Diesel Engine Horsepower	750	230
Outlet Area (m^2)	4.67	1.17
Thrust Range (kg)	118-593	26-133
Heat Range (kcal/sec)	472-4720	126-1260
Max Exhaust Temp (^oC)	222	264
Max Exhaust Vel (m/sec)	37.8	36.6

El Toro, CA. An array of 24 thermistors, as shown in Figure 4, was installed downstream of the combustors. Fifteen thermistors were installed in a horizontal array 3 m above the ground. Five thermistors and single component wind sets were mounted every 3 m on each of the two 15 m towers. The closer tower is positioned at the near edge of a hypothetical runway and the far tower at the centerline of a 45 m wide runway. A reference wind set and thermistor were mounted about 150 m from the site and outside the area affected by the combustors. Although it would have been desirable to place thermistors more than 80 m from the large combustor, this was not practical because of the extremely hilly terrain beyond this point. All data were fed into a 100 channel data acquisition system and recorded on magnetic tape. In many of the tests that were conducted at night, smoke was introduced into the plume, illuminated with a search light, and then photographed. These pictures, an example of which is shown in Figure 5, provided a means of determining the areal extent of the heat plume. Subjective measurements of lift-off distances were also made for each test by physically feeling the heat plume and determining where it appeared to lift off the ground. By combining these three forms of data, a reasonable picture of the heat plume from the runway and approach zone combustors can be obtained, as illustrated in Figures 6 and 7. The shaded area in the upper portion of the figures represents the vertical cross-sectional area outlined by the smoke. The bottom portion shows the temperature rise contours for the 3 m level. The temperature rises represent one-minute averages, whereas the lift-off distance and plume profile, as defined by the smoke, represent 10-15 sec averages.

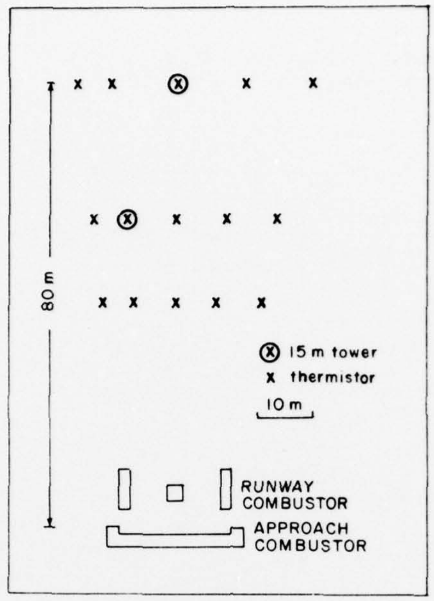

Figure 4. Layout of Combustors and Thermistors at El Toro Test Facility

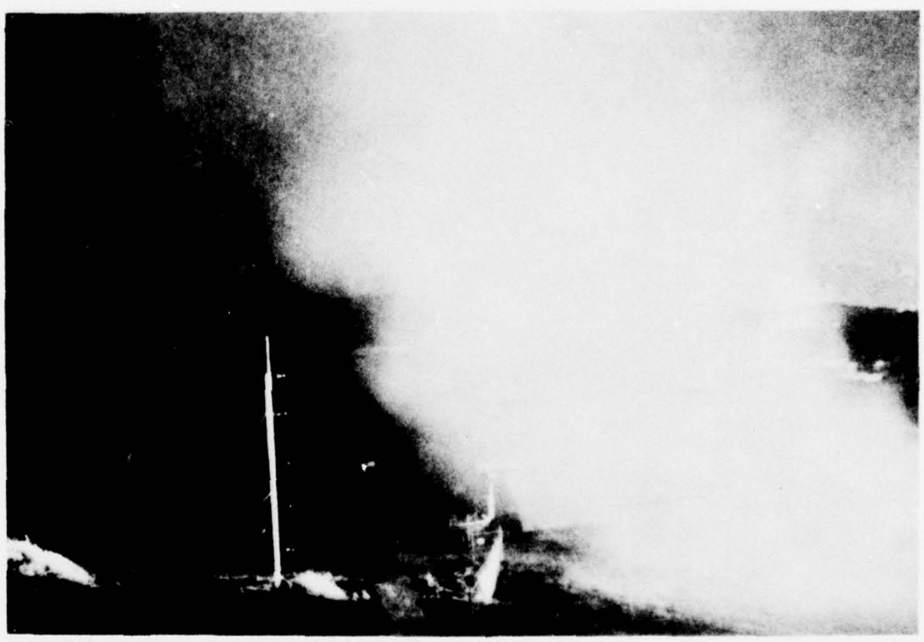

Figure 5. Photograph of Runway Combustor Illuminated by Smoke and Searchlight

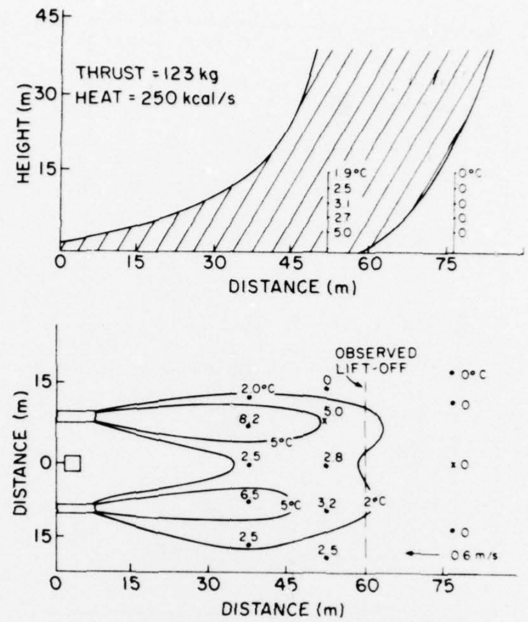

Figure 6. Top and Side Views of Runway Combustor Heat Plume as Depicted by the Smoke and Thermistors

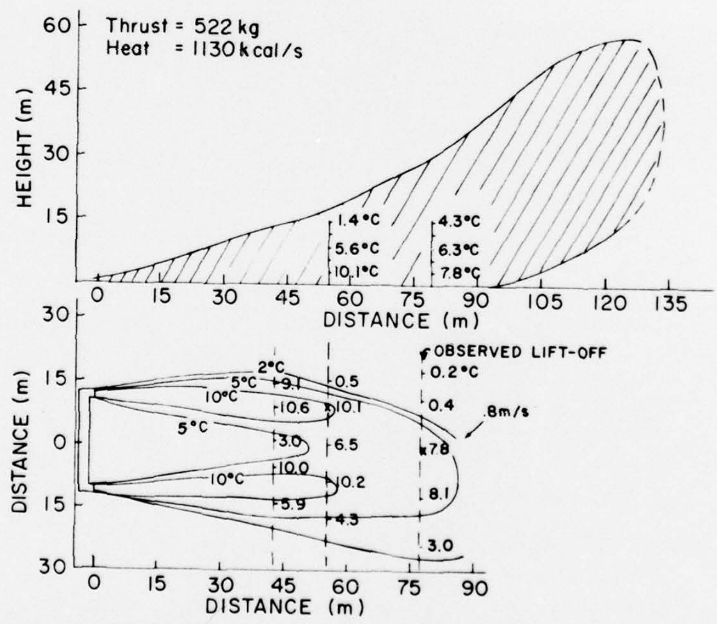

Figure 7. Top and Side Views of Approach Zone Combustor Heat Plume as Depicted by the Smoke and Thermistors

Tests were conducted at night in clear air under a variety of heat, thrust, thrust angle and wind conditions. Tests were restricted to times when the winds were generally less than 2 m/sec. Crosswinds, or winds perpendicular to the combustor flow, were restricted to 0.5 m/sec or less. As it turned out, 95 percent of the tests were conducted with a headwind as opposed to a tailwind. There were 127 tests conducted with the runway combustor and 165 tests with the approach zone combustor. Each test lasted for a period of 3-5 min.

To determine the appropriate heat output for fog clearing, the combustors were operated at various heat settings and the temperature changes (ΔT) were observed. It was assumed that temperature rises of 2-3^{o}C were adequate to clear the fog. Since temperature measurements were made only up to the 15 m height one can only conjecture as to the heat requirements for clearing higher than 15 m. The subscale tests indicated heat requirements of 283 and 420 kcal/sec per runway combustor outlet for clearing depths of 15 m and 30 m respectively, and 1589 kcal/sec per approach zone combustor outlet for a clearing depth of 60 m. These values assume combustors on both sides of the runway and approach zone. Operating the runway combustor near the two heat outputs produced temperature rises of 4-5^{o}C at the near tower and 2^{o}C at the far tower when the plume reached that far. Operating the approach zone combustor at the above heat output resulted in maximum ΔT's of approximately 11^{o}C and 7^{o}C at the near and far tower, respectively. In both cases, this would appear to be adequate heat for clearings to depths of 30 and 60 m. Therefore, based on the restricted measurements of the full-scale tests, the heat requirements derived from the 1974 subscale tests appear to be reasonably valid.

Thrust settings were also varied to determine the appropriate thrust settings for various heat outputs and wind conditions. The observed lift-off distances were compared with the subscale and theoretical results. It was determined from the tests that the lift-off point D, occurred when plume centerline height, Z, was approximately equal to 0.17D. These distances were compared with the trajectory derived from the round jet model described by Klein and Kunkel[24] and with the subscale projection distances, defined in full scale as the plume distances when the centerline heights are equal to 7.8 m. Figure 8 shows a comparison of the full scale, subscale and theoretical lift-off distances for both the small and large combustors. The full-scale test results are an average of all tests in which the heat outputs were close to the optimum heat setting described above. In most cases the wind was a headwind and averaged 0.5 m/sec. Five different thrust settings on each combustor were used during the tests. Lift-off points beyond 80 m were difficult to measure because of the hilly terrain, and therefore, the lift-off distances at the three higher thrust settings on the large combustor are approximate. The subscale results are based on a 0.5 m/sec headwind. However,

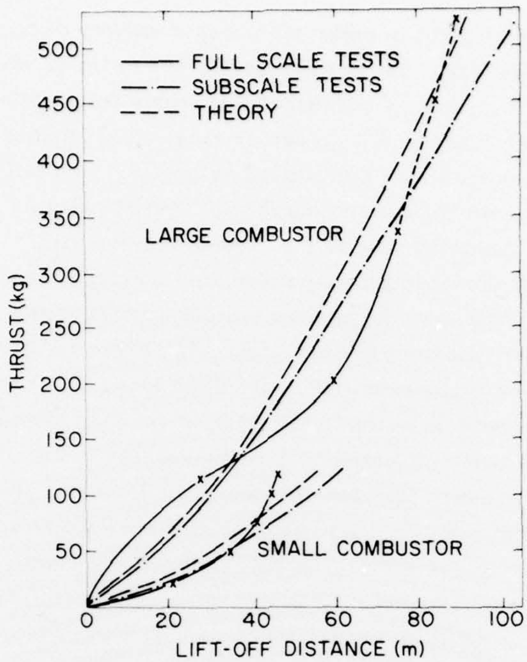

Figure 8. Lift-Off Distance as a Function of Thrust for Both Combustors as Derived from Full Scale and Subscale Tests and From Theory

the theoretical results are based on zero wind since the model is not designed for headwind cases. The plume from the larger combustor shows shorter distances than the plume from the smaller combustor for a given thrust because of its higher heat output and consequently greater buoyancy. In general, the three approaches show reasonably good agreement. However, the full scale results show a steeper slope at the higher thrust levels. In other words, greater thrust increases are required to increase the distance by a given amount. In fact, during some test sequences, little change was noticed in the plume behavior when going from 60 percent to 100 percent thrust. It is believed that if a line of combustors were used, as they were in the subscale tests, that the lift-off distances at the greater distances would be increased because of the merging of the plumes and the thrust/distance slope would be similar to that of the subscale tests. The low distance observed at the 20 percent thrust setting of the large combustor appears to be real and cannot be easily explained.

The effect of wind speed on the plume trajectory was also determined. In general, the effect was less than that indicated by the subscale tests and the model, as shown in Table 5. The 35 percent reduction in plume lift-off distance

Table 5. Percentage Reduction in Plume Lift-off Distances as Headwind Component Increases From 0 to 1.5 m/sec and Heat Output Increases 10-Fole

	Percent Reduction	
	Wind (0-1.5 m/sec)	Heat (10x)
Subscale	65	65
Theory	55*	65
Full Scale	35	25

*Represents percent change as tailwind decreases from 1.5 to 0 m/sec.

as the headwind increased from 0 to 1.5 m/sec is considered a maximum change. At several combustor settings, wind appeared to have no or very little effect. Some of the scatter and apparent inconsistencies in the data are believed to be due to the fact that, because of the hilly terrain, the reference wind was at times not representative of the wind affecting the plume.

The effect of heat output on the plume trajectory was also compared with that predicted by the subscale tests and the model. Again, as with the wind, the effect due to varying heat was less than expected. As illustrated in Table 5, as the heat increases 10-fold, the plume lift-off distance decreases 25 percent while both the model and the subscale tests show a 65 percent decrease.

There is no apparent explanation of this relatively insensitive behavior of the plume to changes in wind and heat. In any case, the reduced dependency on wind and heat is encouraging because it means a more stable plume and, therefore, more persistant clearings than one thought possible based on theory and the subscale results.

The combustors were also operated at different vertical thrust angles to determine its effect on the plume trajectory. Thrust angles could be varied in 15° increments. Those tests were conducted only in tailwind situations. It becomes quite apparent that raising the thrust angle only 15° raised the plume some 15 m off the ground over the target area, at least in tailwinds up to 1.5 m/sec. Higher thrust angles placed the plume well above the two 15 m towers. It would appear that only at those airfields that experience high crosswinds in fog, such as Upper Heyford, would there be a need to vary the vertical thrust angle, and then probably only in a Category I approach zone, where clearings must extend up to 75 m.

6. THERMAL FOG DISPERSAL SYSTEM SPECIFICATIONS

A modern thermal fog dispersal system (TFDS) should consist of three major components — the combustors, the fuel distribution subsystem, and the control subsystem. The TFDS should be fully automated so that it can be operated and monitored from one central control point, thus minimizing the number of operators and providing fast turn-on and turn-off capability in order to conserve fuel. For most efficient and reliable operation, meteorological data should be fed into the control center and used to optimize the combustor settings.

The number and size of combustors will vary depending on the landing category, the runway width and length, and the expected winds in fog at the particular location. Since more than one size combustor is required, because of the varying geometry, there are certain trade-offs that should be considered which would have an impact on costs and complexity. At airfields with light crosswinds or crosswinds from one predominant side, such as Ramstein AB and March AFB, the most economical system may be one which employs one line of larger combustors on the upwind side rather than two lines of small combustors. In the approach zone where the cross-sectional area expands, the most effective system would be one in which the combustors increase in size as the cross-sectional area increases. However, this type of system would not be practical from a production and maintenance standpoint. A more realistic approach would be to vary the spacing between outlets, the spacing decreasing with increasing cross-section thus in effect increasing the heat output per unit length of approach as the cross-section increases. In this study we will assume a maximum of three different-sized combustors.

Based on the results of the full-scale and subscale tests and the theoretical work, combustor specifications were derived for the two landing categories for Ramstein AB. These specifications are shown in Table 6 along with the fuel consumption required to produce the specified heat. It is assumed that combustors are placed on both sides of the runway.

It should be emphasized that there could be many variations to the specifications in Table 6. Various trade-offs, depending primarily on costs, can be made between spacing and distance from centerline and segment length, all of which affect the heat and thrust output and number of outlets required.

The maximum thrust is that thrust required to project the heat into the volume on the near side of the centerline in calm or parallel wind conditions. In a crosswind situation the upwind combustors will cover more of the clearing volume while the downwind combustors will cover less. At some point, approximately 2 m/sec, the downwind combustors can be shut off and all the clearing can be done by the upwind combustors. In this situation, the heat output of the upwind

Table 6. TFDS Combustor Specifications for Category I and Category II Landing Systems at Ramstein AB

Zone	Avg Heat Output (kg)	Max. Thrust (kg)	Spacing (m)	No. of Outlets	Dist. from Centerline (m)	Length (m)	Fuel Consumption (1/min)
			CATEGORY I				
1	2000	600	22-31	52	125	699	740
1	1250	450	20-30	44	105	546	392
2	575	150	15-22	32	75	300	131
2	350	150	15-22	64	75	600	159
3	283	150	21	146	75	1540	295
				338		3685	1717
			CATEGORY II				
1	1250	450	24-30	36	105	546	321
2	575	150	18-26	28	75	300	115
2	350	150	18-26	54	75	600	134
3	283	150	21	146	75	1540	295
				264		2986	865

combustors should be about double the average heat output, thus maintaining a constant heat output per unit length of runway. To allow for crosswind situations, the maximum heat output of each outlet should then be twice the average output. It will be noted that there are five different heat output specifications for a Category I system. However, one burner could be designed to operate at the three lower heat settings, thus maintaining the requirement of no more than three different-sized combustors.

The spacing of the combustors was adjusted to take into account the less stringent RVR requirements for Category II and for the rollout of a Category I landing system. Using Allard's law and the relationship between extinction coefficient and drop size concentration, and assuming a worse case of 100 m RVR, it can be shown that most of the drops must be evaporated to achieve 800 m RVR while 84 percent must be evaporated to achieve 400 m RVR. For higher initial RVRs the percentage would be lower. To achieve 84 percent clearing, the number of combustors can be decreased by 16 percent, thus resulting in an increase in spacing of 19 percent.

The distance from the centerline was based on the fact that the distance between the combustors and the edge of the clearing zone should be at least 2.5 times the spacing between outlets in order to assure adequate merging of the plumes. This, however, would not be required for achieving 400 m RVR where complete merging is not necessary.

Table 6 clearly shows the advantages of a Category II TFDS over a Category I TFDS. The need for large thrustors is eliminated, the number of combustors is reduced by 22 percent and, probably most importantly, the fuel consumption is reduced by 50 percent.

The other six bases have longer and/or wider runways and, therefore, would require somewhat larger fog dispersal systems. The wider approach zone of a 90 m wide runway would require combustors on the order of 700 kg of thrust instead of the 600 kg required for the narrower approach. Larger combustors would not be required along the wider runway if absolute clearing is not required along the edges of the runway and if the underground combustors can be placed just 30 m from the runway edge — the same distance from the centerline as for the 45 m wide runway. It is the opinion of the author that, in the rollout zone, the pilot need only see the centerline and, therefore, does not need an unrestricted view of the lights along the runway edge. Assuming 22 m spacing of the combustor outlets, approximately 50-60 percent of the volume will be cleared along the runway edge thus allowing the pilot, under the worst possible visibility conditions, to see the edge lights at least 50 percent of the time.

It should be emphasized that the specifications given in Table 6 are based on subjective interpretation of the experimental and theoretical results and, therefore, may not be optimum. Additional testing in fog, using two rows of combustors with 6 to 8 outlets per row and adequate visibility and wind instruments, would be desirable in order to further optimize the size and orientation of the combustors. If conditions warrant the immediate installation of a TFDS, it is recommended that the heat and thrust specifications be increased approximately 20 percent to provide a safety margin.

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